



Performance Evaluation of CPCs Using Corrosion Sensors – Laboratory and Field Studies

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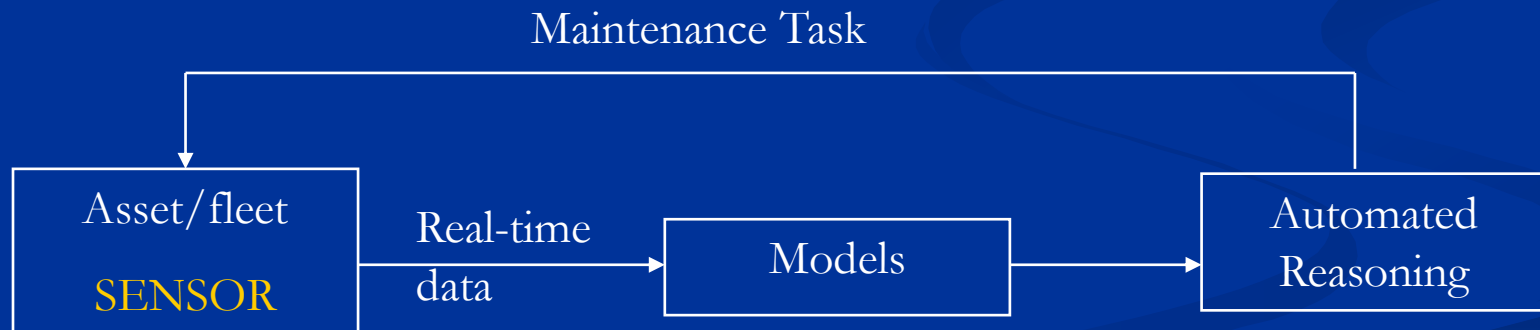
Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 04 FEB 2009		2. REPORT TYPE		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Performance Evaluation of CPCs Using Corrosion Sensors - Laboratory and Field Studies				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX, 78238-5166				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES 2009 U.S. Army Corrosion Summit, 3-5 Feb, Clearwater Beach, FL					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 30	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Outline

- Introduction
- Laboratory Evaluations
- Field Evaluations
- Summary

Condition Based Maintenance

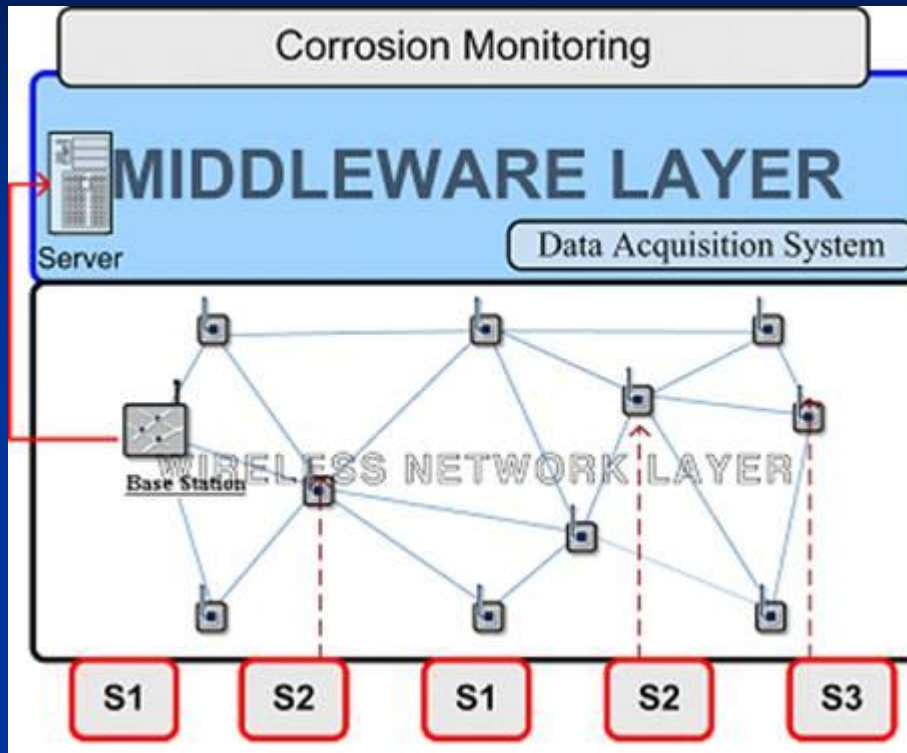
- Goal: reduce inspection cost, while maximizing safety and readiness – optimize maintenance intervals
- Uses real-time data to prioritize and optimize maintenance resources



Motes Based Technology

- Based on miniature computer platform (motes) containing TinyOS2 operating system.
- Advantages:
 - localized control at each sensor
 - external triggers can be used to activate sensors (e.g., environmental change, signal from other motes or from control hub)
 - on-board data storage
 - on-board communications
 - motes network can optimize data transmission, i.e., allows intelligent distributed sensor network
 - automated data acquisition

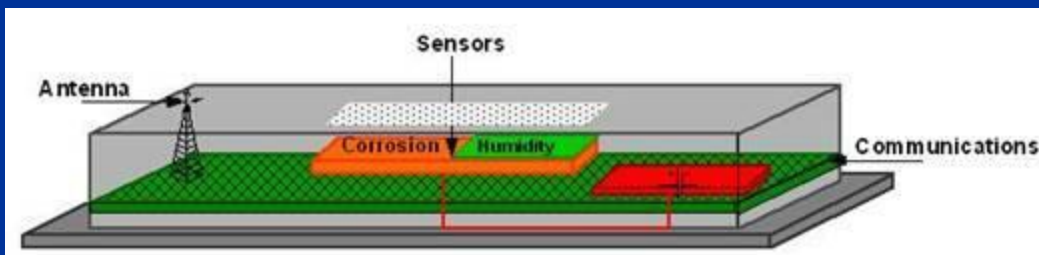
Data Transmission



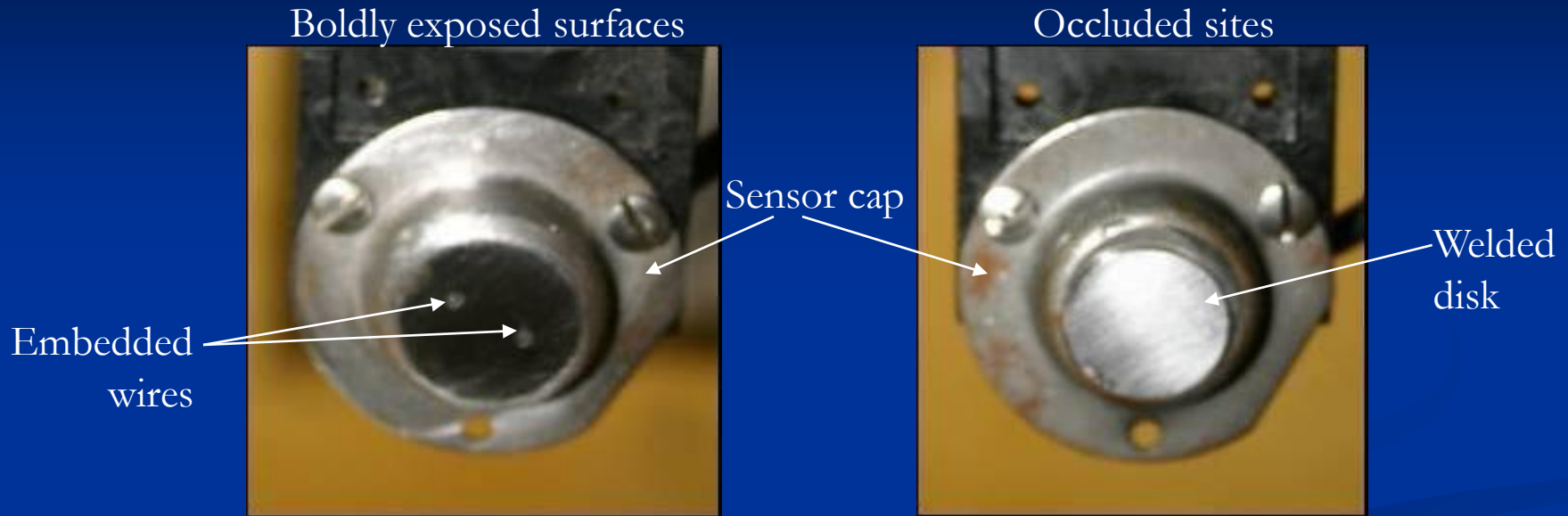
Base station connected to web portal through data network

Data routed to base station through reader network

Autonomous sensors – data collection at programmed intervals



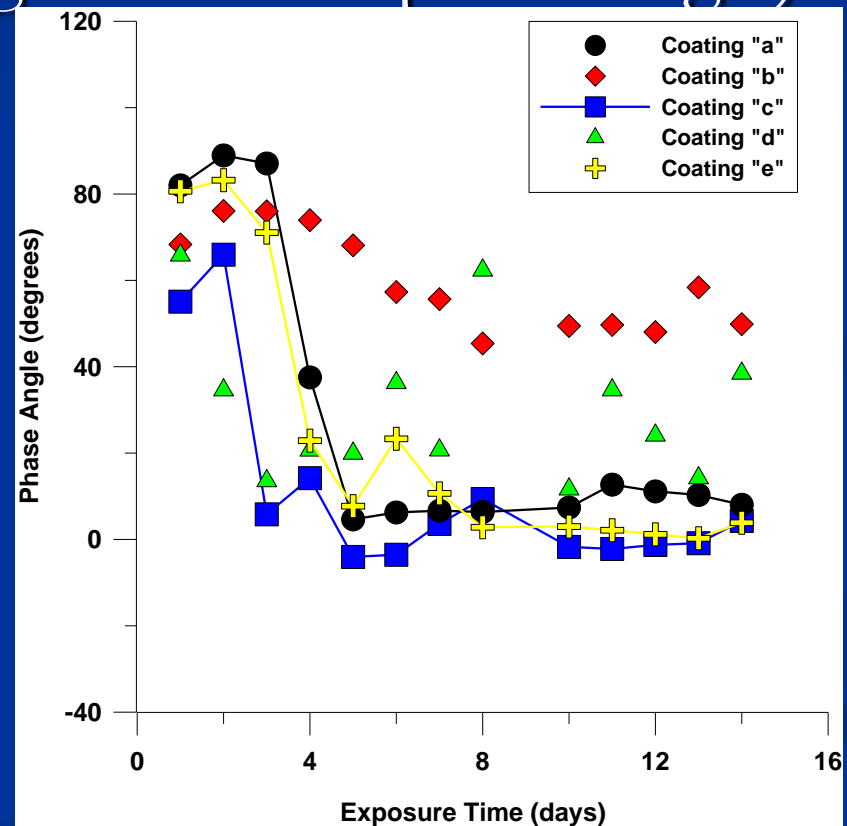
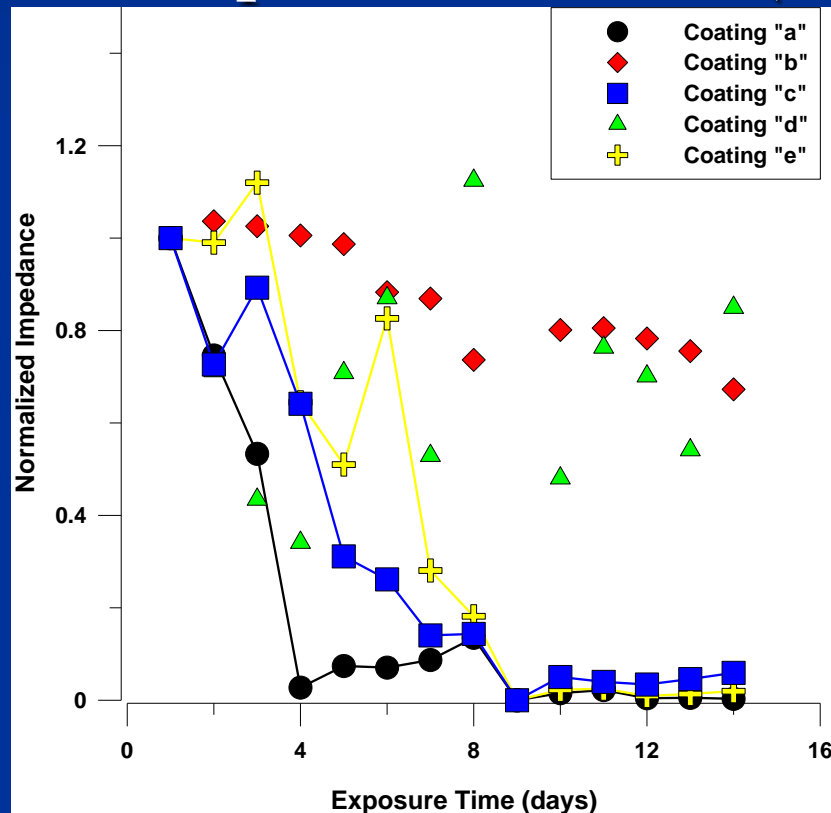
Coating Degradation Sensor (CDS)



- Based on EIS
- Changes in impedance magnitude and phase angle values correlate with coating degradation
- Measurement at single frequency
- Rapid data acquisition and analysis

CDS Operation Principle

- Coating degradation is indicated by a drop in impedance values (magnitude and phase angle)



J. Dante, K. Price, A. Sabata and B. Sabata, "Embedded Coating Degradation Sensors for Monitoring Performance of Temporary Coatings", CORROSION 2007, Paper No. 07387.

Army Corrosion Summit, 2009

February 4, 2009

Clearwater Beach, FL

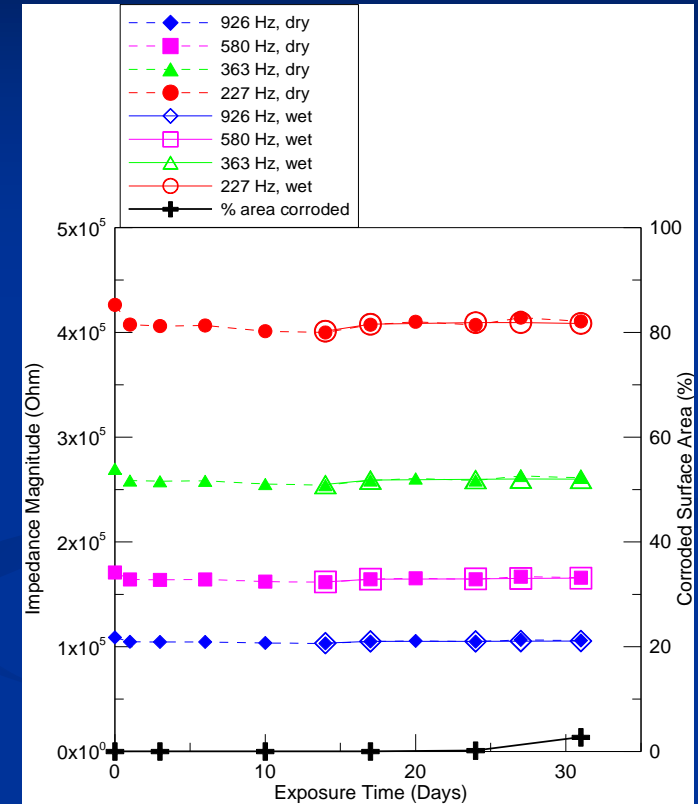
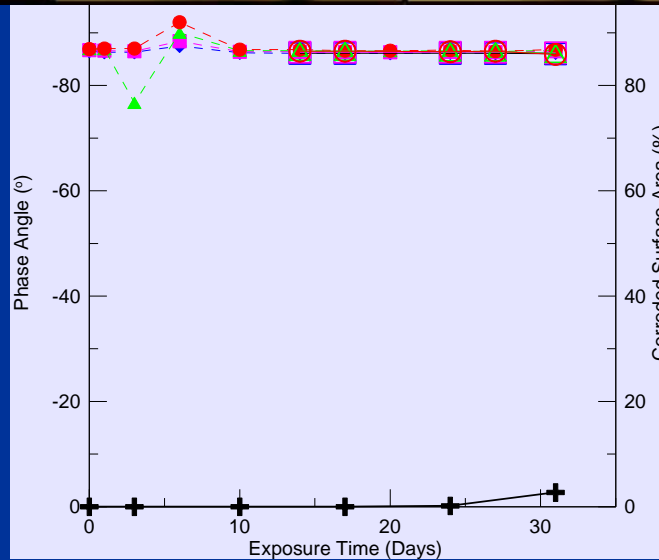
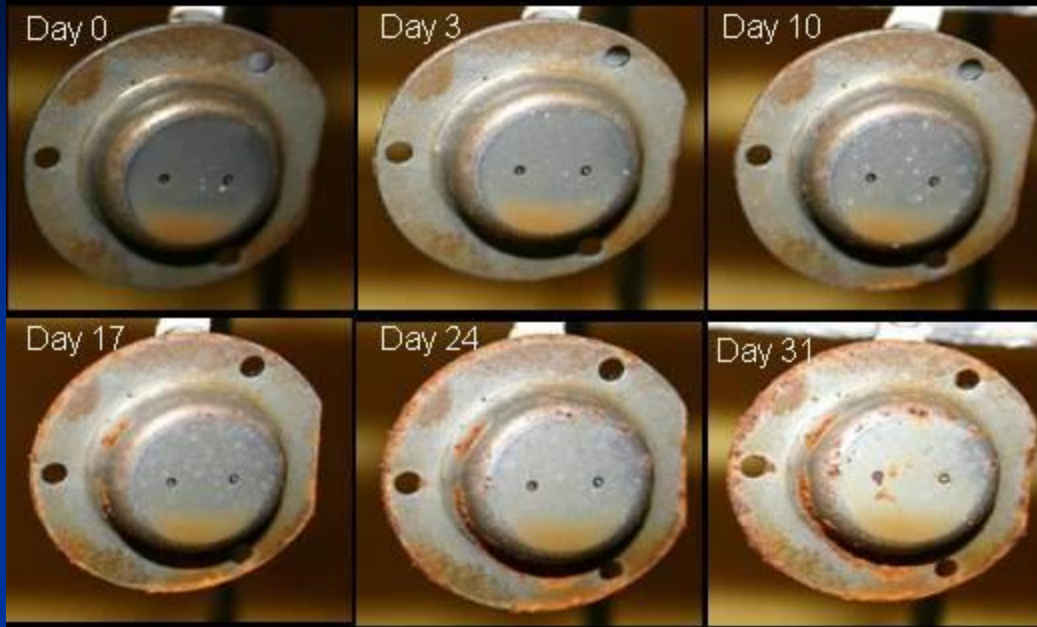
Laboratory Tests

- Performed in Accelerated Exposure Testing (AET) chamber for 31 days
- Temperature: 30 °C
- Relative Humidity: 6 hrs @ 50 % and 6 hrs @ 90 %
- Salt spray: 15 sec every other day
- Salt solution composition: 0.9 wt% NaCl + 0.1 wt% CaCl₂ + 0.25 wt% NaHCO₃

Electrochemical Impedance Tests

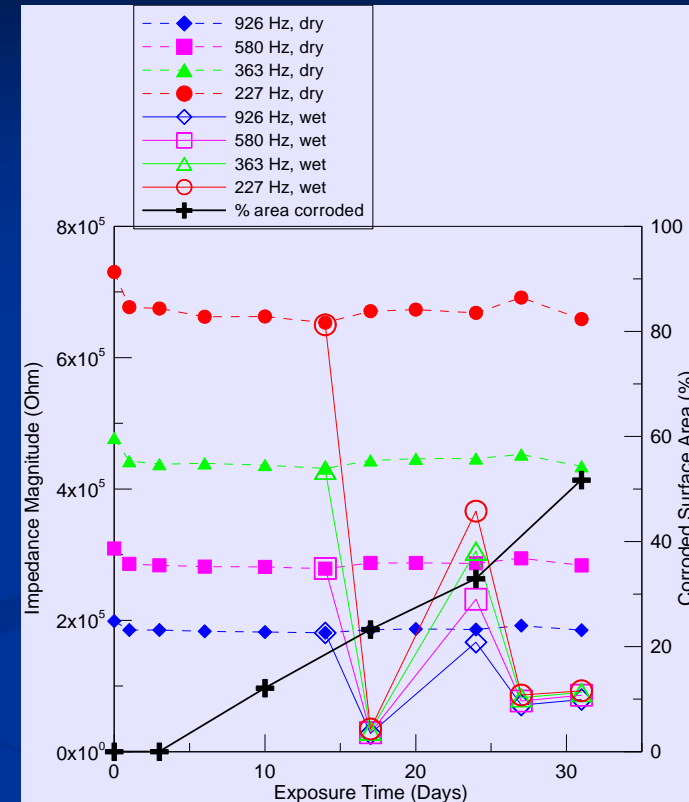
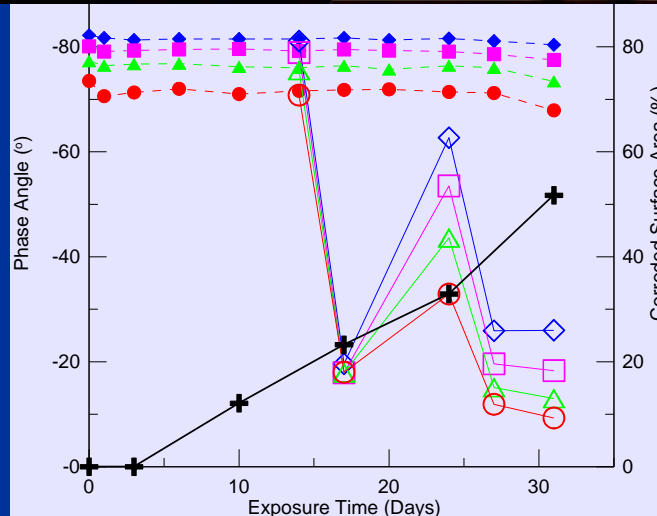
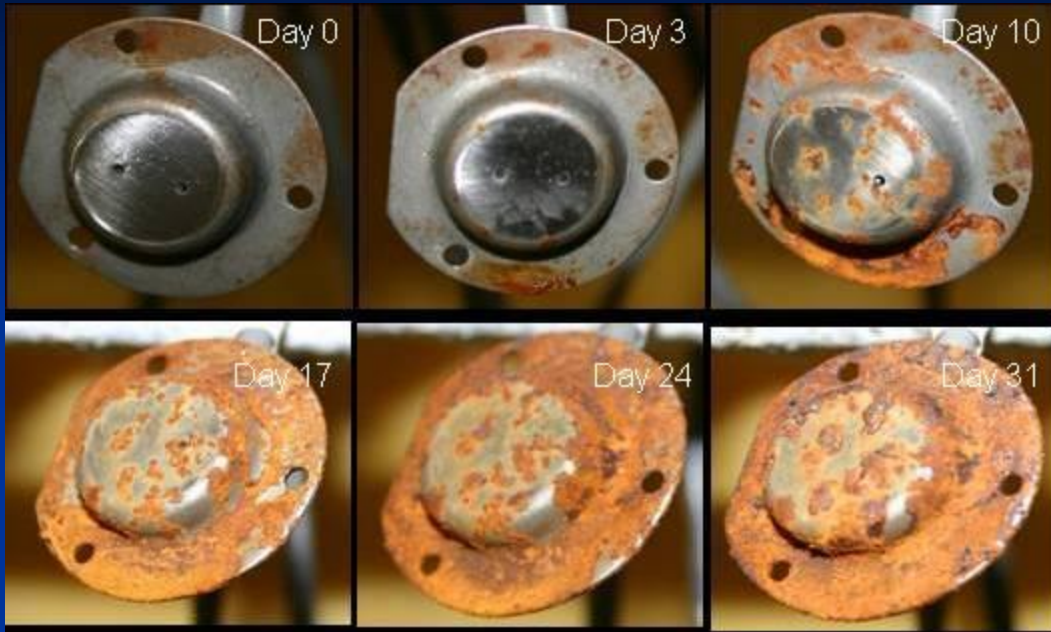
- Full impedance spectra measured at days 0, 3, 10, 17, 24 and 31
- Frequency range: $0.05 - 10^5$ Hz
- AC amplitude: 20 mV and 200 mV
- DC bias: 0 mV
- Impedance Magnitude and Phase Angle were determined at 227, 363, 580 and 926 Hz

Results – “The Good”



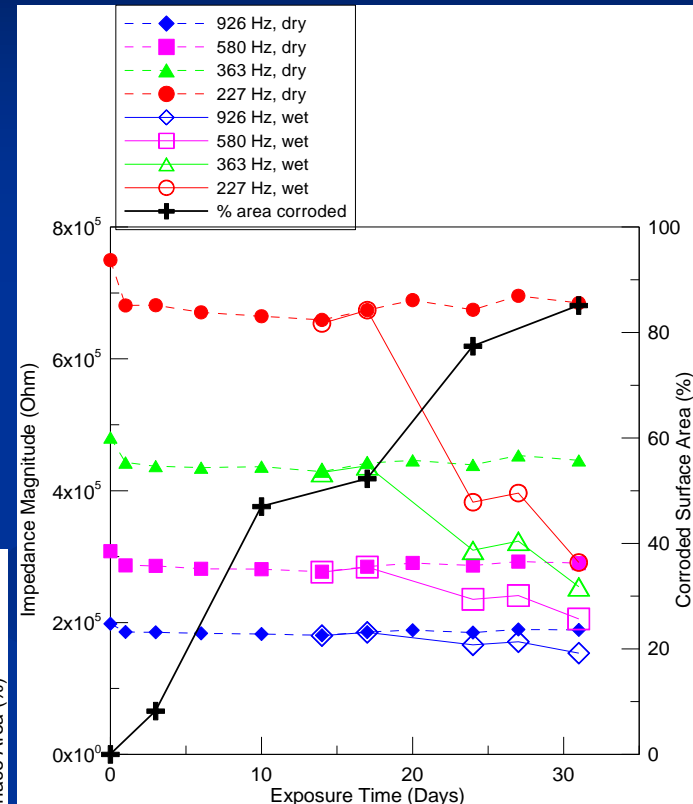
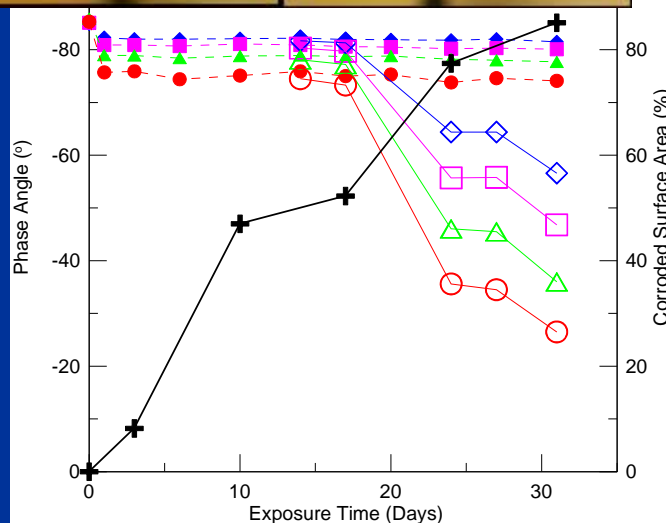
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Clearwater Beach, FL

Results – “The Bad”



Army Corrosion Summit, 2009
Clearwater Beach, FL

Results – “The Ugly”



Results - Summary

CPC	Threshold % area corroded	Recovery during wet part of cycle	Recovery during dry part of cycle	First visual sign of corrosion	Sensor signal indicating corrosion
<i>CPC A</i>	60 %	No	Yes	3 days	~18 days
<i>CPC B</i>	5 %	No	No	17 days	17 days
<i>CPC C</i>	> 2 %	No	Yes	31 days	31+ days
<i>CPC D</i>	20 %	Some	Yes	3 days	< 14 days
<i>CPC E</i>	40 %	Some	Yes	3 days	17 days
<i>CPC F</i>	20 %	Some	Yes	10 days	17 days
<i>CPC G – 2 pins</i>	20 %	No	Yes	10 days	< 14 days
<i>CPC G – 4 pins</i>	20 %	No	No	2 days	5 days

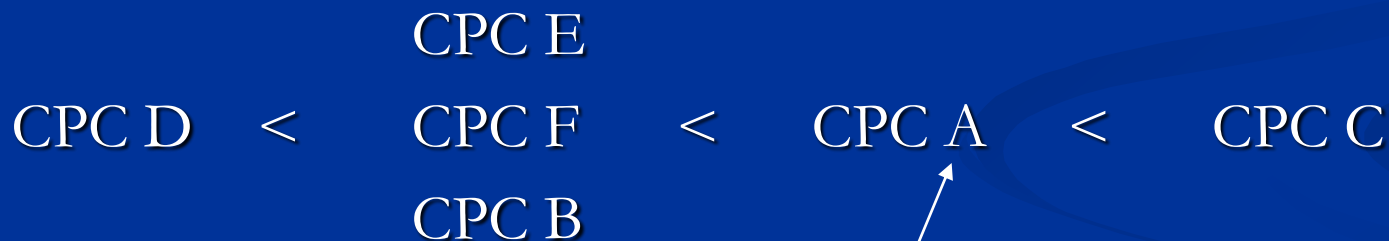
Ranking of CPCs – Visual and Impedance

- Visual:

CPC A < CPC D < CPC E < CPC F < CPC B < CPC C

- Impedance (sensor output):

CPC E
CPC D < CPC F < CPC A < CPC C
CPC B

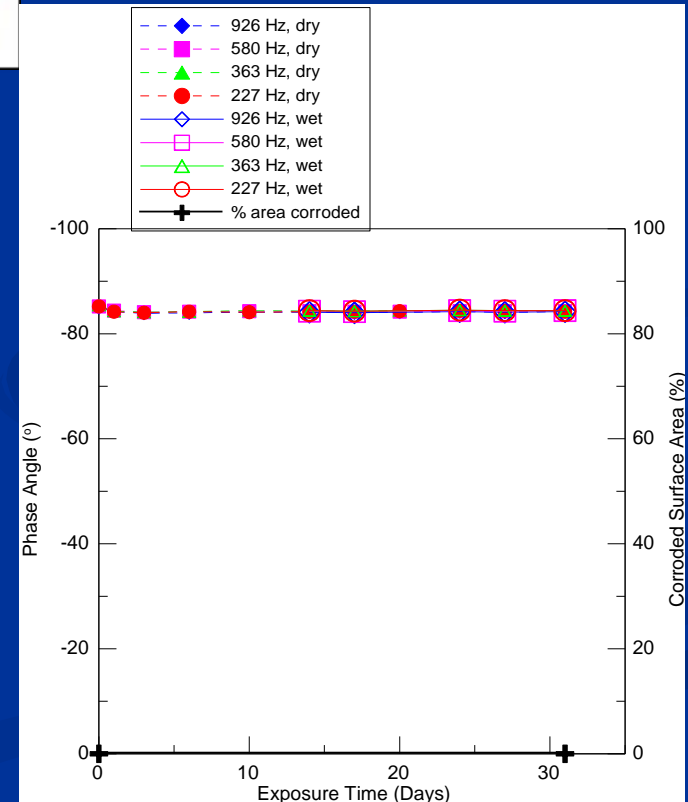
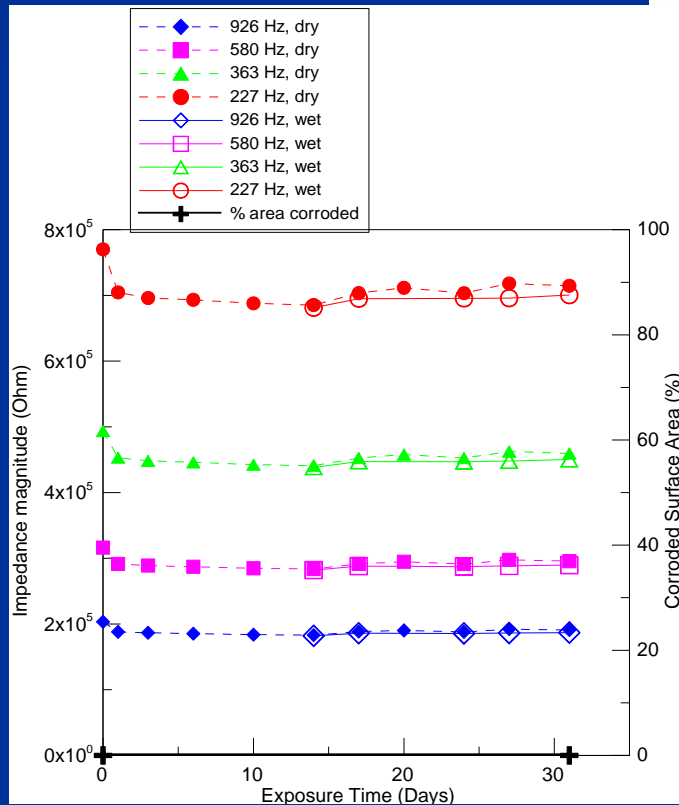


Formation of rust layer that is impermeable to moisture??

Depth of corrosion damage is also important!

Occluded Sites

Treatment with CPC prior to exposure



Field Studies

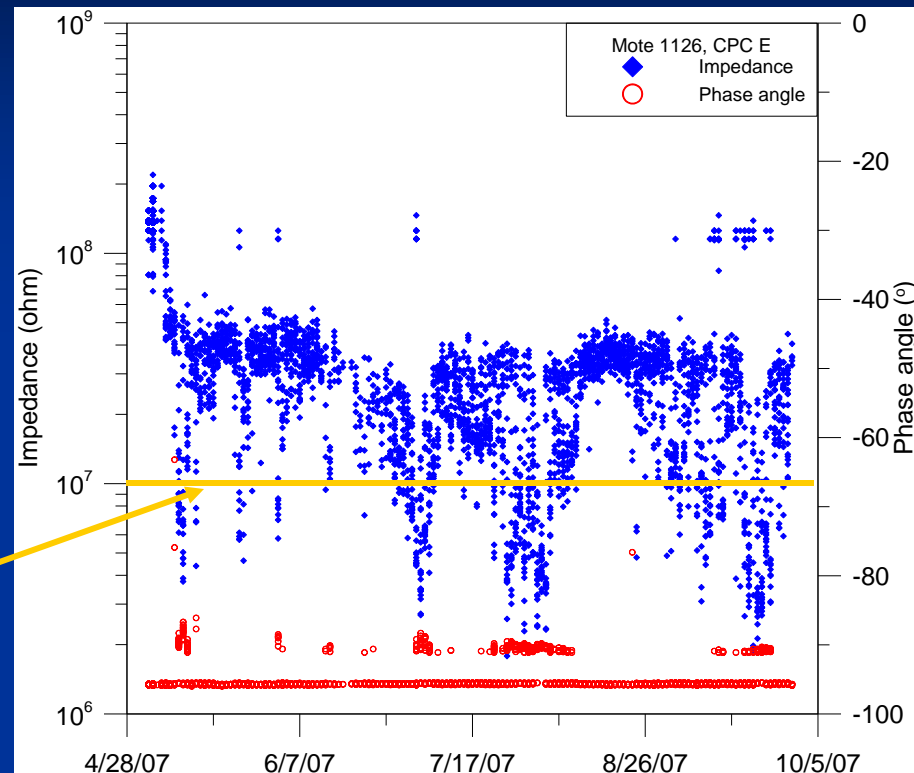
- Sensors exposed to coastal environment at Daytona Beach, FL for 149 days.
- Sensor package acquired and wirelessly transmitted relative humidity, temperature and impedance data to a web portal.
- EIS parameters:
Frequency: 1000 Hz
AC amplitude: 200 mV
Measurement interval: once every hour



Results – The “Bad”



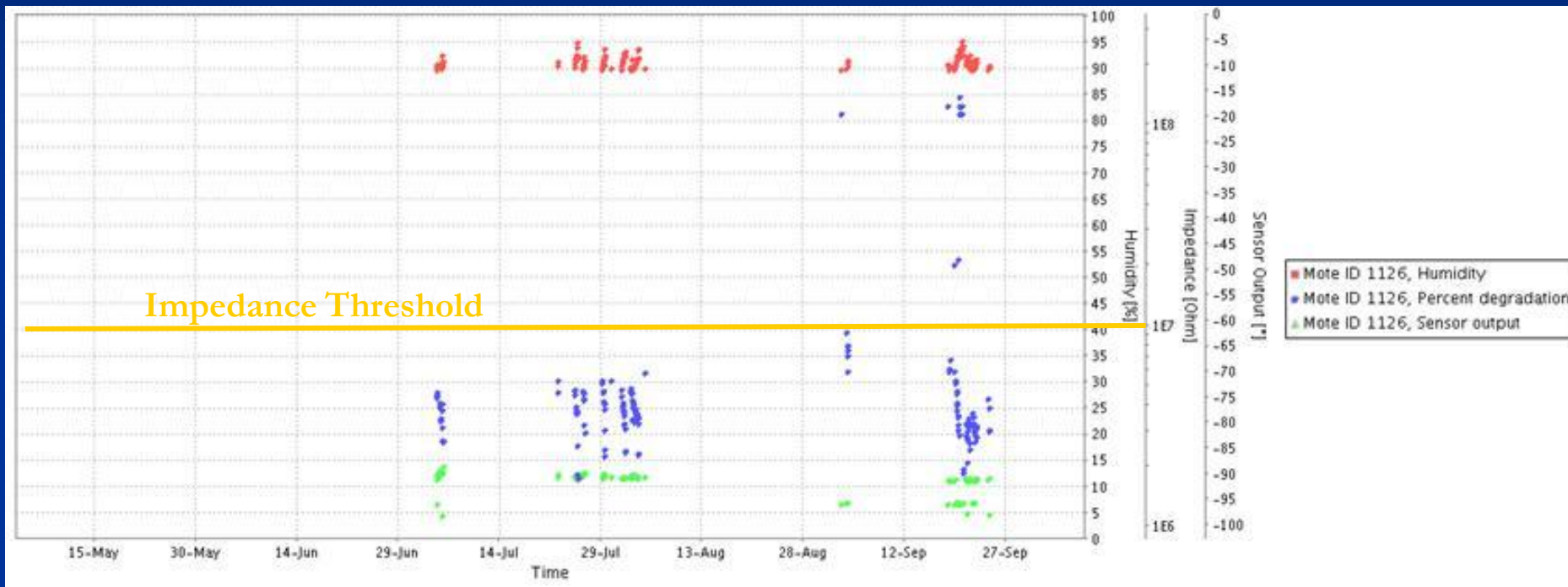
Impedance
threshold



- Initial drop in impedance is due to water uptake.
- Coating failure: drop of impedance below $10^7 \Omega$.
- Recovery: during low RH periods, sensor surface dries out.
- Phase angle changes follow impedance magnitude trends.

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Sensor Output, RH: 80-100 %

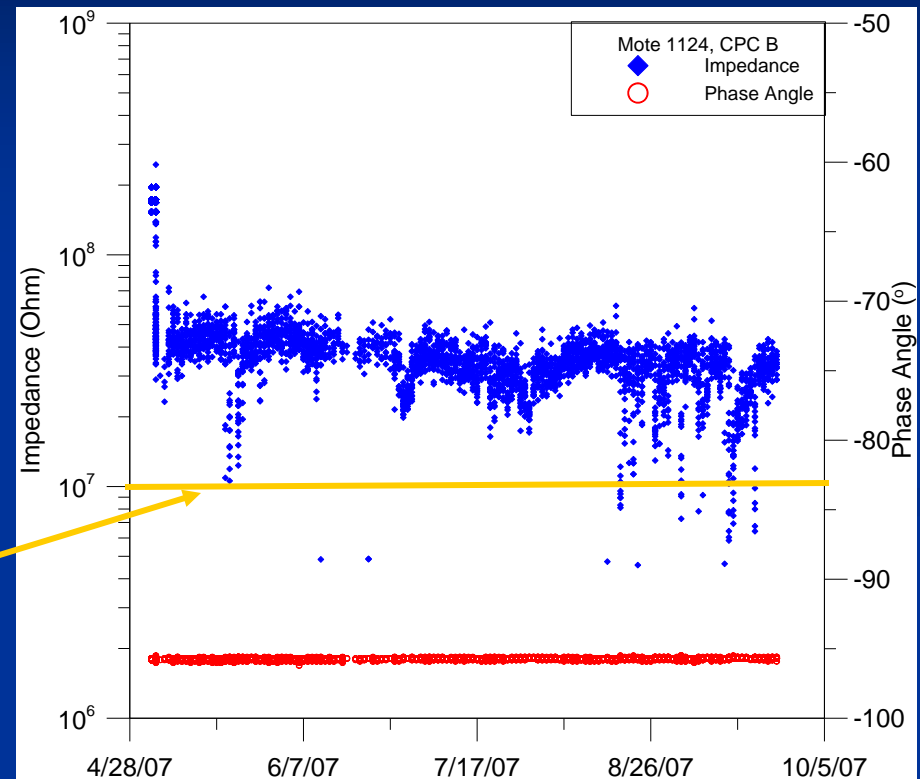


- Most significant changes.
- Water condensation + salt deposits – high conductivity medium for corrosion.

Results – “The Good”



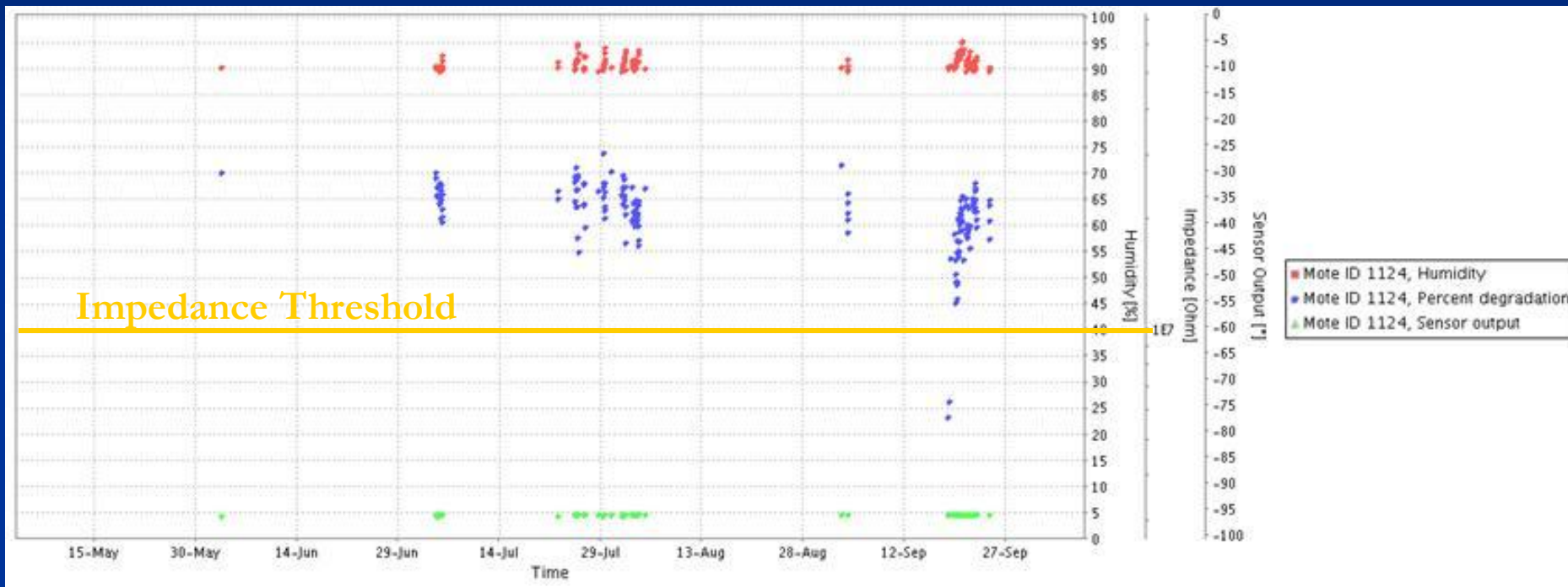
Impedance
threshold



- Initial drop in impedance is due to water uptake.
- No corrosion is observed on treated top surface.
- No significant drop of impedance below threshold.
- No change of phase angle.

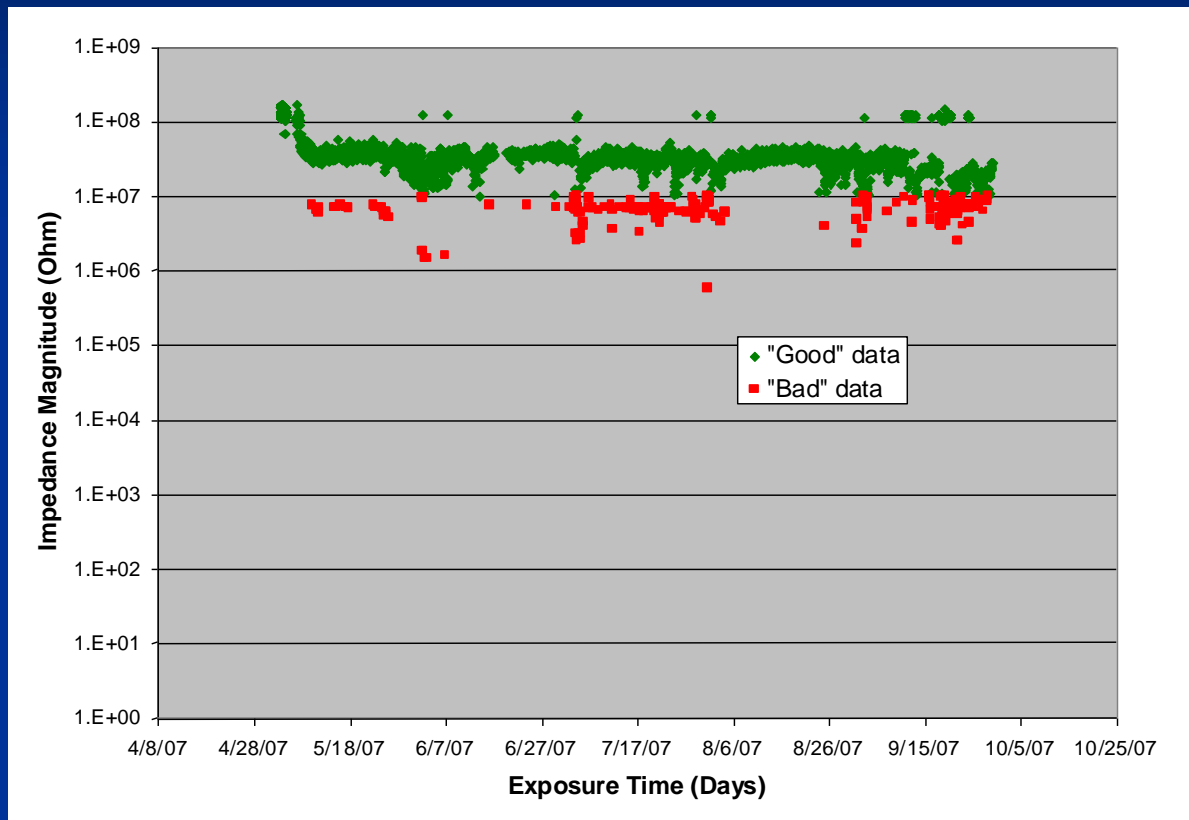
Army Corrosion Summit, 2009
Clearwater Beach, FL

Sensor Output, RH: 80-100 %



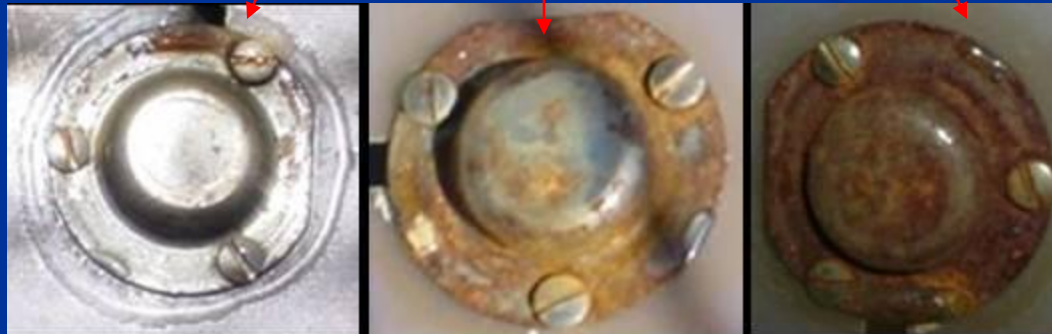
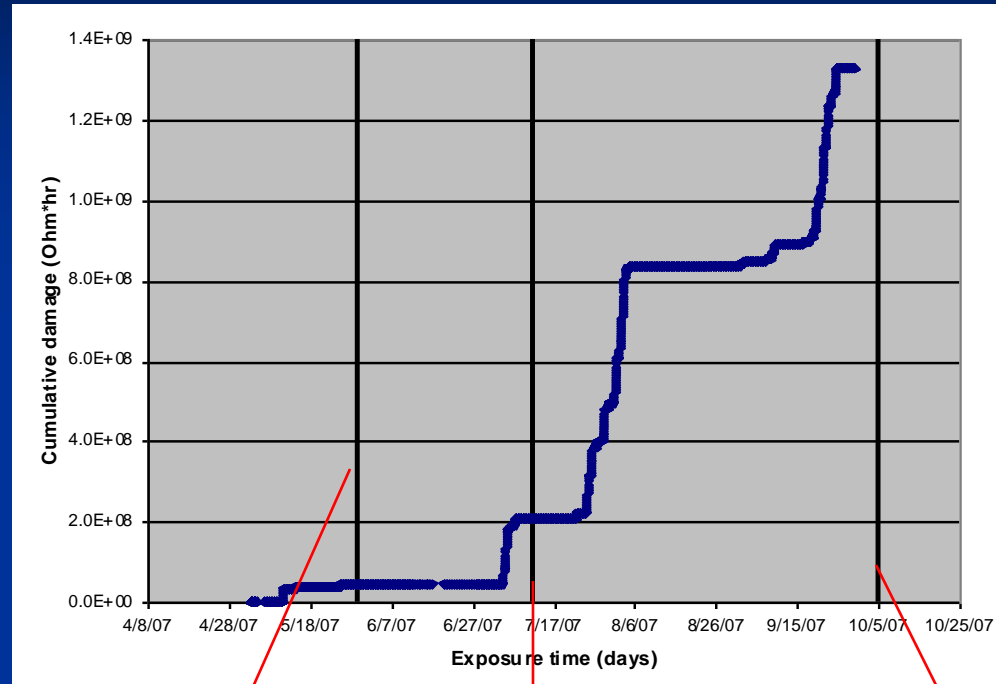
- No drop below impedance threshold for up to 110 days.
- No change in phase angle.
- This CPC provides excellent corrosion protection even under high humidity conditions.

Cumulative Damage Analysis



$$\text{Cumulative Damage} = \int_0^t \left| 10^7 - \text{Impedance Magnitude}_{\text{if } I < 10^7 \Omega} \right| dt$$

Cumulative Damage Analysis



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Results - Summary

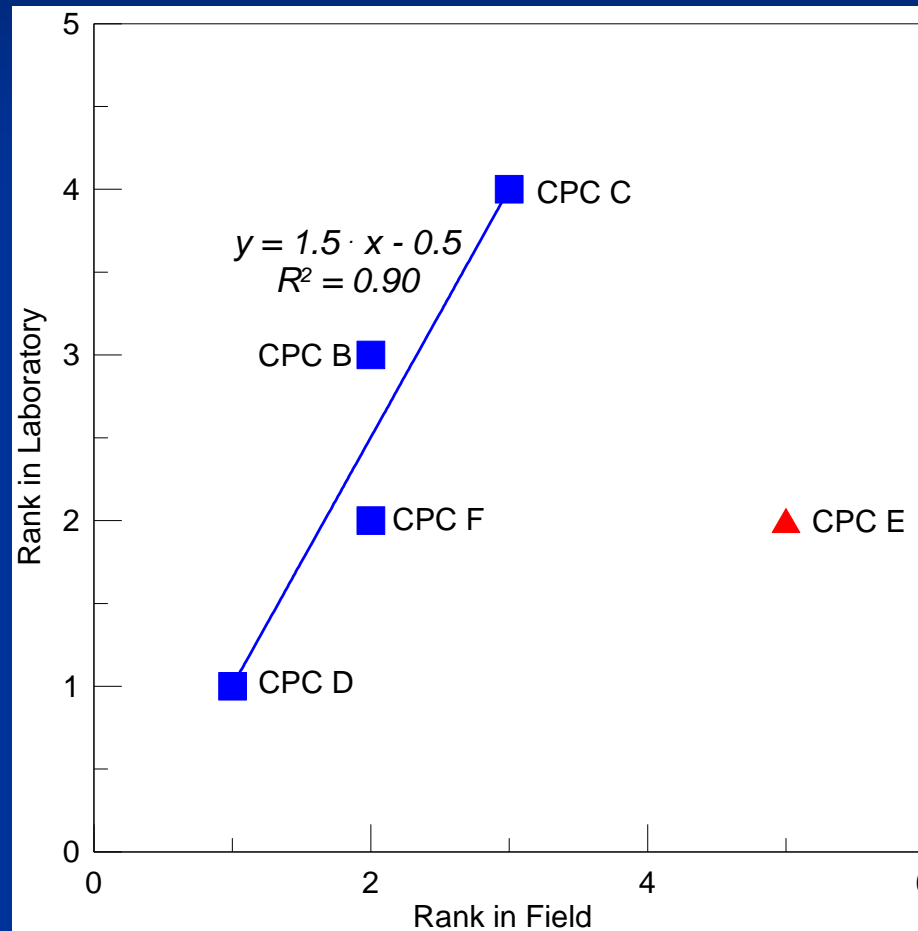
Ranking based on cumulative damage:

$$\text{CPC D} < \text{CPC F} < \text{CPC B} < \text{CPC C} < \text{CPC E}$$

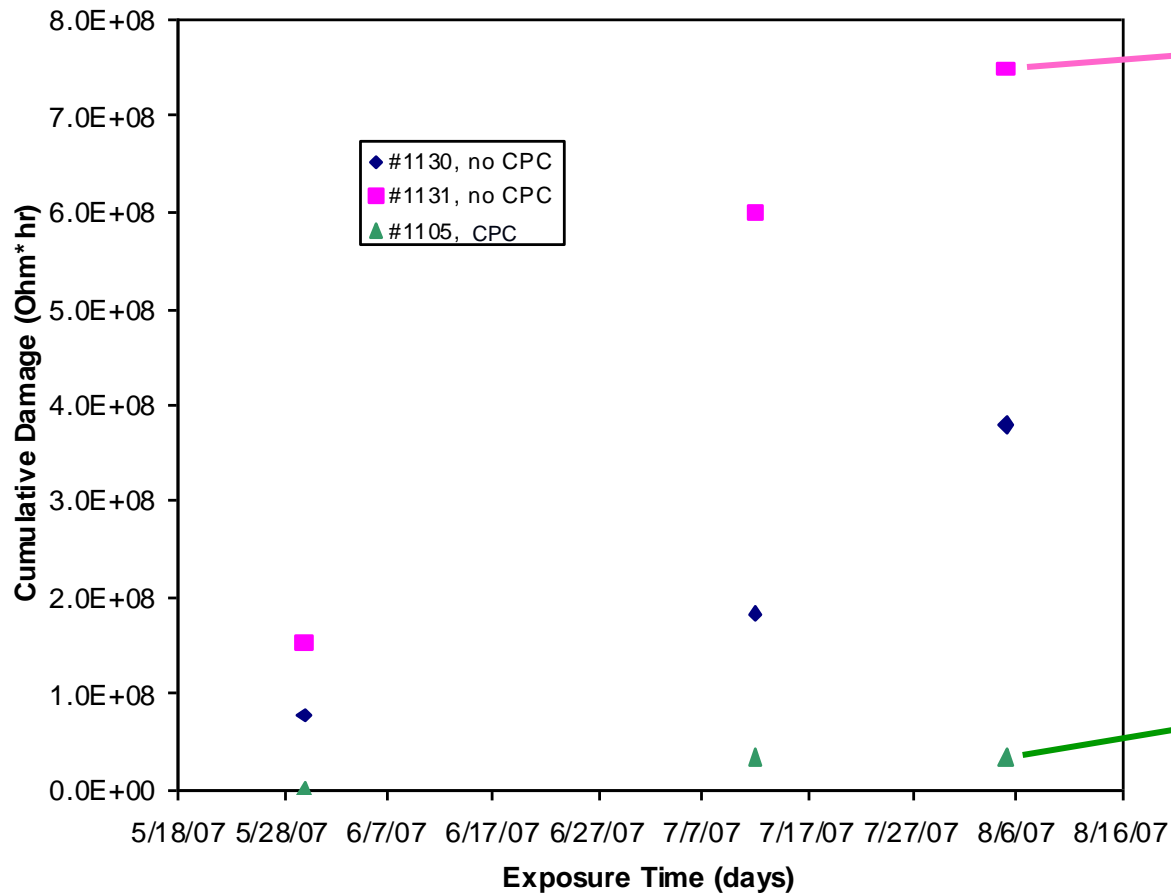
Ranking based on visual observations:

$$\text{CPC D} = \text{CPC B} < \text{CPC F} < \text{CPC C} < \text{CPC E}$$

Performance Ranking of CPCs: Cyclic lab test vs. Daytona Beach field test



Occluded Sites



Web Portal

Aginova monitoring system - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Forward Stop Reload Home Search Favorites Mail Print Address Bar

Address http://64.251.8.128/aginova/main.jsp?selectedLocation=23

Welcome (admin) Admin | Log out

Home Infrastructure Analytic reports Administration Customize this view

Overview

Location: Kaneohe Bay, HI

Sensor Nodes Relay Nodes

Sensor nodes

Mote ID	Location	Last seen	Last data	Graphs	Comment
1115	Fence-Kbay	31 days ago	-7 sec ago		-
1121	Tension fabric shelter	10 min 12 sec ago	13 min 50 sec ago		-
1123	Tension fabric shelter	1 min 1 sec ago	33 min 58 sec ago		-
2018	Fence-Kbay	3 days ago	3 days ago		-
2019	Fence-Kbay	5 days ago	5 days ago		-
1190	radiator	14 min 33 sec ago	16 min 20 sec ago		-
1174	Rear suspension	7 min 23 sec ago	1 h 0 min ago		-
1194	Passenger side step	25 days ago	25 days ago		-
1192	support rail underneath	25 days ago	25 days ago		-

Done Internet

start Aginova monitoring s... Inbox - Microsoft Out... 7:47 PM

Web Portal

Aginova monitoring system - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Forward Stop Home Search Favorites Refresh Print Mail Internet Options

Links Customize Links Free Hotmail Windows Windows Marketplace Windows Media

Address http://64.251.8.128/aginova/main.jsp?selectedVehicle=34

Overview List of sensor nodes

Sensor nodes for MT592265


Mote ID	Location	Degradation level	Last seen	Last data	Graphs	Comm
1167	Passenger side step	N/A	6 h 25 min ago	6 h 55 min ago		-
1169	Box Support in rear pass wheel well	N/A	6 h 57 min ago	6 h 57 min ago		-

[Back to the main view](#)

Sensor Locations

Sensor ID and data links

Ass



Summary

- It was determined that impedance based coating degradation sensors can be successfully used to detect coating failure and assess the performance of CPCs in coastal environments.
- Laboratory tests showed that the changes associated with coating failure are more pronounced at lower measurement frequencies.
- The sensitivity of the sensor was found to be dependent on the performance of the CPC; better sensitivity was found in case of better performing CPCs.
- The changes in impedance parameters measured during the wet part of the exposure cycle were found to correlate well with visual observations of surface corrosion. In some cases, recovery of the impedance values during the dry part of the cycle was observed.

Summary

- No significant improvement in sensitivity was found when the number of sensor wires embedded in the surface was increased from two to four.
- Field testing of sensor packages at Daytona Beach, FL indicated that it is feasible to collect and wirelessly transmit temperature, relative humidity and impedance data using mote based sensor technology.
- A data analysis method was developed to assess the performance of CPCs based on sensor output.
- The order of performance of different CPCs determined from sensor output in the field and laboratory was found to be in agreement.

Acknowledgements

- The work reported here was sponsored by the U. S. Marine Corps Corrosion Prevention and Control (CPAC) Program Office.
- The author acknowledges the guidance provided by Mr. Matthew Koch, USMC CPAC and Mr. Hancel Porterfield.
- The author also acknowledges the technical assistance provided by Mr. Albert Faz in the laboratory tests and Mr. Bill Abbott in the field tests as well as guidance provided by Dr. Ashok Sabata.